Transportation Research Part C 62 (2016) 1–20

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Enhancing the performance of existing urban traffic light control through extremum-seeking

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 5 August 2015
Accepted 28 October 2015
Available online 7 December 2015

Keywords:
Extremum-seeking
Adaptive control
Traffic control
Online calibration

ABSTRACT

Urban traffic light controllers are responsible for maintaining good performance within the transport network. Most existing and proposed controllers have design parameters that require some degree of tuning, with the sensitivity of the performance measure to the parameter often high. To date, tuning has been largely treated as a manual calibration exercise but ignores the effects of changes in traffic condition, such as demand profile evolution due to urban population growth. To address this potential shortcoming, we seek to use a newly developed extremum-seeker to calibrate the parameters of existing urban traffic light controllers in real-time such that a certain performance measure is optimised. The results are demonstrated for three categories of traffic controllers on a microscopic urban traffic simulation. It is demonstrated that the extremum-seeking scheme is able to seek the optimal parameters, with respect to a certain performance measure, for each of these traffic light controllers in an urban, uni-modal traffic environment.

1. Introduction

There have been major developments in intelligent control of urban traffic lights over the last few decades. These advanced control strategies have been implemented either in a traffic simulator or in real life with varying degrees of success reported under different operating conditions. An ideal urban traffic light control strategy should be able to cope with all traffic conditions, namely undersaturated, saturated or oversaturated. Furthermore, it should be adaptive to real-time traffic conditions and robust against disturbances, such as traffic demand fluctuations, accidents, road works or special events. Therefore, recent development of urban traffic light control follows the trend of using some real-time measurements as feedback in a closed-loop (online) control strategy to correct for measured changes in the traffic.

A closed-loop (online) traffic light control can be classified as model based or non-model based. A model based controller uses a prediction model of the traffic system to find an appropriate traffic light input. Two common examples of model based strategies are: rolling horizon model predictive control (Henry et al., 1983; Gartner, 1983; Mirchandani and Head, 2001; Tettamanti and Varga, 2010; Lin et al., 2012; Aboudolas et al., 2010) and linear quadratic regulator/integrator (LQR/I) (Diakaki et al., 2002; Aboudolas and Geroliminis, 2013). A rolling horizon model predictive control (MPC) coupled with the use of a high-fidelity model results in a computational-heavy controller. Hence, the use of MPC is limited to controlling

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http://dx.doi.org/10.1016/j.trc.2015.10.016
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one intersection or a few at best (Henry et al., 1983; Henry, 1989; Gartner, 1983; Boillot et al., 1992; Mirchandani and Head, 2001). To address this computational issue, linear models are utilised (Diakaki et al., 2000; Dinopoulou et al., 2000; Bielefeldt et al., 2001; Diakaki et al., 2002, 2003; Dinopoulou et al., 2006; Papageorgiou et al., 2006; Lin et al., 2009; Aboudolas et al., 2010; Lin et al., 2010, 2011), which typically use ''averaged'' parameters, and the performance of the controller is dependant on how well these parameters are approximated.

When the concern is emphasised on the congestion in the whole network rather than looking at each individual street, it is also possible to model the whole network as a group of smaller regions, where each region is modelled by an aggregate dynamical equation that uses the concept of the Macroscopic Fundamental Diagram (MFD). A MFD describes the relationship between vehicle accumulation and the flow within a traffic network. Among other literature on MFD (Wardrop, 1968; Godfrey, 1969; Herman and Prigogine, 1979; Mahmassani et al., 1987; Ardekani and Herman, 1987; Daganzo, 2007), analysis has revealed that the shape of MFD is concave (Daganzo and Geroliminis, 2008) and it has been verified by experimental results (Geroliminis and Daganzo, 2008). Further studies for different scenarios of urban traffic networks also show that the concave nature of the MFD always presents (Aboudolas et al., 2010; Zhang et al., 2013; Geroliminis et al., 2014). Therefore, this is exploited in a perimeter control scheme (Aboudolas and Geroliminis, 2013; Keyvan-Ekbatani et al., 2012, 2013; Haddad and Shraiber, 2014; Keyvan-Ekbatani et al., 2015; Ramezani et al., 2015), which essentially is a gating strategy that limits the incoming traffic flow such that the vehicle accumulation in each region stays close to its critical value that leads to optimal throughput/flow of the network. Perimeter control schemes use vehicle conservation models, where the number of vehicles that complete their trips (throughput) is predicted by using the MFD and the number of vehicles that enter the network is restricted by the perimeter control. The goal of perimeter control is to regulate the vehicle accumulation within the network to a set-point. However, since the MFD of the network might vary for different traffic conditions (Zhang et al., 2013), the performance of the controller largely depends on the set-point that is manually selected.

On the other hand, an online non-model based approach establishes ''rules'' to be followed. Some examples are: SCATS (Lowrie, 1982) and self organising traffic lights (SOTL) (Gershenson, 2005; de Gier et al., 2011). Similar to the other traffic light controls, an online non-model based controller's performance depends on its tuning parameters, such as offset, or maximum cycle time in the case of SCATS (Lowrie, 1982), and threshold value in the case of SOTL (de Gier et al., 2011; Zhang et al., 2013). Therefore, regardless of whether the controller is model based or model-free, the use of a parameter adaptation technique as an augmentation to these controllers is potentially beneficial to their performances. In fact, there are some previous works that have investigated parameter adaptation of traffic light controllers.

The adaptation techniques that were used in existing literature for adapting the parameters of traffic light controllers are SPSA and its modification (referred to as the AFT technique) (Spall, 1992, 2003; Maryak and Chin, 2008; Spall and Chin, 1994, 1997; Chin et al., 1999; Kosmatopoulos et al., 2008a,b; Kosmatopoulos, 2009; Kouvelas et al., 2011). These works incorporate the parameter adaptation scheme as a higher level control in a hierarchical manner, where the SPSA is performing a higher-level control on the existing traffic light controller by providing parameters to optimise its performance. However, there has not been any rigorous stability proof of either SPSA and AFT applied to systems with dynamics; and extending the existing stability result to include dynamical systems might be a challenge due to the discrete nature of these techniques. Therefore, it is proposed to use an extremum-seeking technique for the parameter adaptation, since its stability has been rigorously guaranteed for application on dynamical systems.

Extremum-seeking (ES) is a non-model based steady-state optimisation scheme for dynamical plants. An ES controller regulates the input of a dynamical plant to the value that optimises the steady-state output (i.e. cost or performance measure) of the plant, without requiring knowledge of the underlying dynamics. In order to achieve this, ES requires several components, namely the dither signals, the gradient estimator, and the optimiser operating in progressively slower timescales. There are many ways to realise these components (Spall, 1992; Krstić and Wang, 2000; Chichka et al., 2006; Srinivasan, 2007; Moase et al., 2010; Liu and Krstić, 2010), the simplest of which is outlined by Tan et al. (2006). While there have been a multitude of ES applications demonstrated over the past decade, the vast majority are on low dimensional (usually single-input single-output) systems.

In the case of controlling the traffic lights of an urban network, the number of parameters typically grows with network size, which along with communication considerations, motivates the use of a decentralised approach of ES. A type of a multi-input multi-output (MIMO) ES scheme that can solve this kind of problem is the Nash equilibrium seeking (NES) (Stanković et al., 2010; Frihauf et al., 2011; Kutadinata et al., 2015). Kutadinata et al. (2015, in preparation) demonstrate the stability of a NES scheme acting on a class of hybrid systems, thereby bridging the gap introduced by previous application of SPSA and AFT to a similar problem.

This paper extends the study of Kutadinata et al. (2014) and investigates the benefit of using a NES scheme for fine-tuning the parameters of several existing urban traffic light control strategies, as illustrated in Fig. 1. This paper investigates the calibration of the parameters of three existing urban traffic light controllers taken from the closed-loop model-free and model-based families of traffic controllers: SCATS's internal and orthogonal offsets; SOTL's threshold value; and the density set-point of a perimeter control. The remainder of this paper is organised as follows. Section 2 outlines the NES scheme used, and is followed by the description of the simulation set up in Section 3. The rest of the paper outlines the simulation results of calibrating perimeter control (Section 4), SCATS (Section 5), and SOTL (Section 6).